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Enhancement of processing gain by selection of acceptance parameters applied to detection of signals buried in noise

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Monterey, California, Naval Postgraduate School

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

ENHANCEMENT OF PROCESSING GAIN BY SELECTION
OF ACCEPTANCE PARAMETERS APPLIED TO DETECTION
OF SIGNALS BURIED IN NOISE

by

James Devens Barron

December 1978

~~is~~ Advisor   G. H. Marmont

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The nature and merits of Tegulometric Frequency Analysis (TFA)
in determining the presence of weak signals in a noise background
have been reported in previous works [1-6]. TFA is based on the
statistical properties of the signal plus noise. Frequency is
determined by a zero crossing technique. Due to the complex nature
of the beating phenomenon in narrowband filtered signal plus noise
waveforms, it has not been possible to satisfactorily describe TFA
in analytical terms. This thesis presents the results of an

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experimental investigation of the feasibility of a new technique
for detection of a sinusoidal signal in noise by defining
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The selection of these statistical parameters has been demon-
strated to enhance the detection of a weak signal in noise and
produce an effective "processing gain".

ENHANCEMENT OF PROCESSING GAIN

BY SELECTION OF ACCEPTANCE PARAMETERS

APPLIED TO DETECTION OF SIGNALS BURIED IN NOISE

by

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Lieutenant, United States Navy
B.S., United States Naval Academy, 1971

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

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                         Dean of Science and Engineering

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The nature and merits of Tegulometric Frequency Analysis
(TFA) in determining the presence of weak signals in a noise
background have been reported in previous works /1-6/. TFA
is based on the statistical properties of the signal plus
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Due to the complex nature of the beating phenomenon in narrow-
band filtered signal plus noise waveforms, it has not been
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a sinusoidal signal in noise by defining acceptance parameters
for amplitude and constancy of frequency. The selection of
these statistical parameters has been demonstrated to enhance
the detection of a weak signal in noise and produce an
effective "processing gain".

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I. INTRODUCTION

A. BACKGROUND

Tegulometric Frequency Analysis (TFA) was developed by
Dr. George Marmont in 1973 at the Naval Postgraduate School,
Monterey, California. The analysis determines the presence
of weak signals in a noise background. The method of analysis
is based on the statistical properties of the signal plus
noise. In this method the time between negative to positive
zero crossings is converted to frequency. A histogram is
produced which contains the count of the occurrence of each
frequency as determined by the algorithm used. The theses
of S. E. Dollar $\underline{/1\underline{/}}$ and W. E. Stockslager $\underline{/2\underline{/}}$ collectively
defined the tegule, provided limited mathematical descriptive
background, and indicated the initial hardware and software
implementations associated with TFA. A detailed description
of TFA is contained in two interim reports by Dr. Marmont
$\underline{/3-4\underline{/}}$. In addition, the processing steps were verified in
1976 by K. A. Tobin $\underline{/5\underline{/}}$.

The "waxing and warning" nature of a narrow band filtered
time domain waveform is shown in Figure 1. This structure
was defined as superimposed tegules. The low amplitude por-
tions of the tegules were observed to randomly contain either
phase reversals or low amplitude shapes. This fact gave
support to the heuristic explanation that the observed large
number of counts associated with weak signals resulted pri-

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Tegule

Phase Reversal

Figure 1

Typical Tegules

marily from counts occurring during tegule depressions due
to noise beating against noise.

B.   OBJECTIVE

The objective of this thesis was to investigate the
feasibility of comparing processed output data to selective
amplitude and constancy of frequency acceptance parameters
to enhance by selection, the detection of a weak signal in a
noise background.   To accomplish this objective the factors
which influence a relatively large histogram count for a
signal frequency compared to the histogram counts associated
with the frequency components of noise had to be identified.
The major work of this thesis was directed towards identifying
these factors.

II. OVERVIEW OF TEGULOMETRIC FREQUENCY ANALYSIS

A. HARDWARE

The particular method used to implement TFA depends upon available hardware. All data was converted to digital form by a twelve bit analog to digital (A/D) converter under the control of a minicomputer. The minicomputer is a Digital Equipment Corporation (DEC) PDP 11/40. A Time/Data FPE4 fast Fourier transform (FFT) microprocessor is attached to the PDP 11/40. The TFA algorithm uses the results of the FFT to accomplish ideal digital filtering and frequency translation. Frequency determination is accomplished in the time domain by a zero crossing technique. One of the characteristics of the Time/Data PFE4 FET is that it is capable of performing complex to complex transforms faster than real to complex transforms. To take advantage of this time saving method one has to perform an initial real to complex DFT followed by a zeroing of the high frequencies in the upper half of the block and a complex to real IFT. Reference 5 contains a more detailed explanation of this procedure. Two DEC RK05 disk drives are used to store the digital data and program routines.

B. HOW TEGULOMETRIC ANALYSIS WORKS AND WHY

The basic program to accomplish TFA is labeled HISCAN. This program contains subroutines which digitally perform the following functions:

1. narrowband filtering of the time domain waveform.

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2. detecting positive going zero crossings.

3. converting the time between positive going zero crossings to frequency.

4. incrementing the count for a detected frequency.

5. equalizing the counts and thus establishing a histogram.

6. limited smoothing of the histogram, if desired.

Equalization is needed, since for a given time period, the counts associated with high frequencies will be larger than those of low frequencies. Equalization is accomplished by multiplying the frequency dependent word in the histogram by a scaling factor whose value decreases with increasing frequency. In this way the amplitude of the histogram becomes a measure of the percentage of time that any given frequency is observed during the analysis period.

The histogram is smoothed by a program which adds successive and adjacent histogram words to produce a running average. The number of frequencies included in this running average is entered as an input variable. Figure 2 shows the output format of the histogram. The horizontal axis is frequency and the vertical axis is proportional to the counts of the individual frequencies.

In dealing with digital information, it is convenient to establish data blocks in multiples of the number $1024=2^{10}$. This is referred to as a 1K block. The blocks are labeled B0, B1, B2, etc. Collectively all of the blocks define the memory

49.5 HZ   50 HZ   50.5 HZ
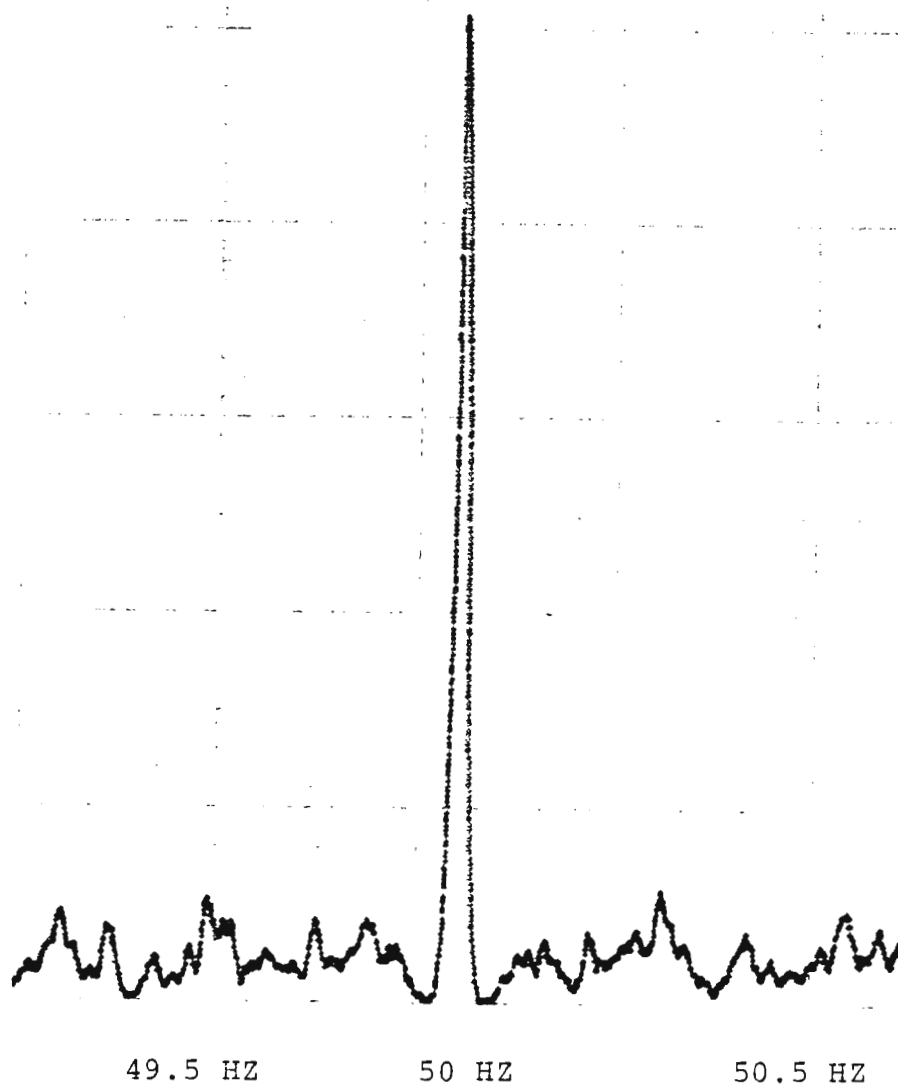
Figure 2

Short Section of TFA HISTOGRAM for S/N = 0 db

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map for the primary program HISCAN. The data flow in HISCAN is shown in Figure 3, which initially appeared in $\underline{/}5\underline{\,/}$. Here a 2K frame of A/D converted data is read from the disk and loaded into the 2K block B0. A copy of the data in B0 is moved to B4. The next sequential 2K frame of data is read from the disk and again stored in B0. A copy of the second 2K frame of data in B0 is loaded into the 2K block B9. In this manner block B0 is used to update the data flow. B4 and B9 collectively form the 4K block B8. Processing starts at this point. As discussed in the previous section, the first step is to get the data into a form where complex to complex transforms can be utilized. This is accomplished by performing a real to complex DFT on block B8. The results are stored in block B8 as shown in Figure 3. The upper half of block B8, which is block B9, is zeroed and a complex to real IFT is performed with the results again being stored in block B8. It should be noted at this time that by zeroing block B9, the analysis is performed on the lower half of the frequency components of the data. If an analysis of the upper half of the frequency components of the data is desired all that is required is a transfer of the contents of block B9 to block B4 prior to zeroing block B9. If this is done, then an analysis of the upper half of the frequency components of the data can continue.

Having performed the above steps, all future transforms are processed as complex to complex. This results in a 63.7

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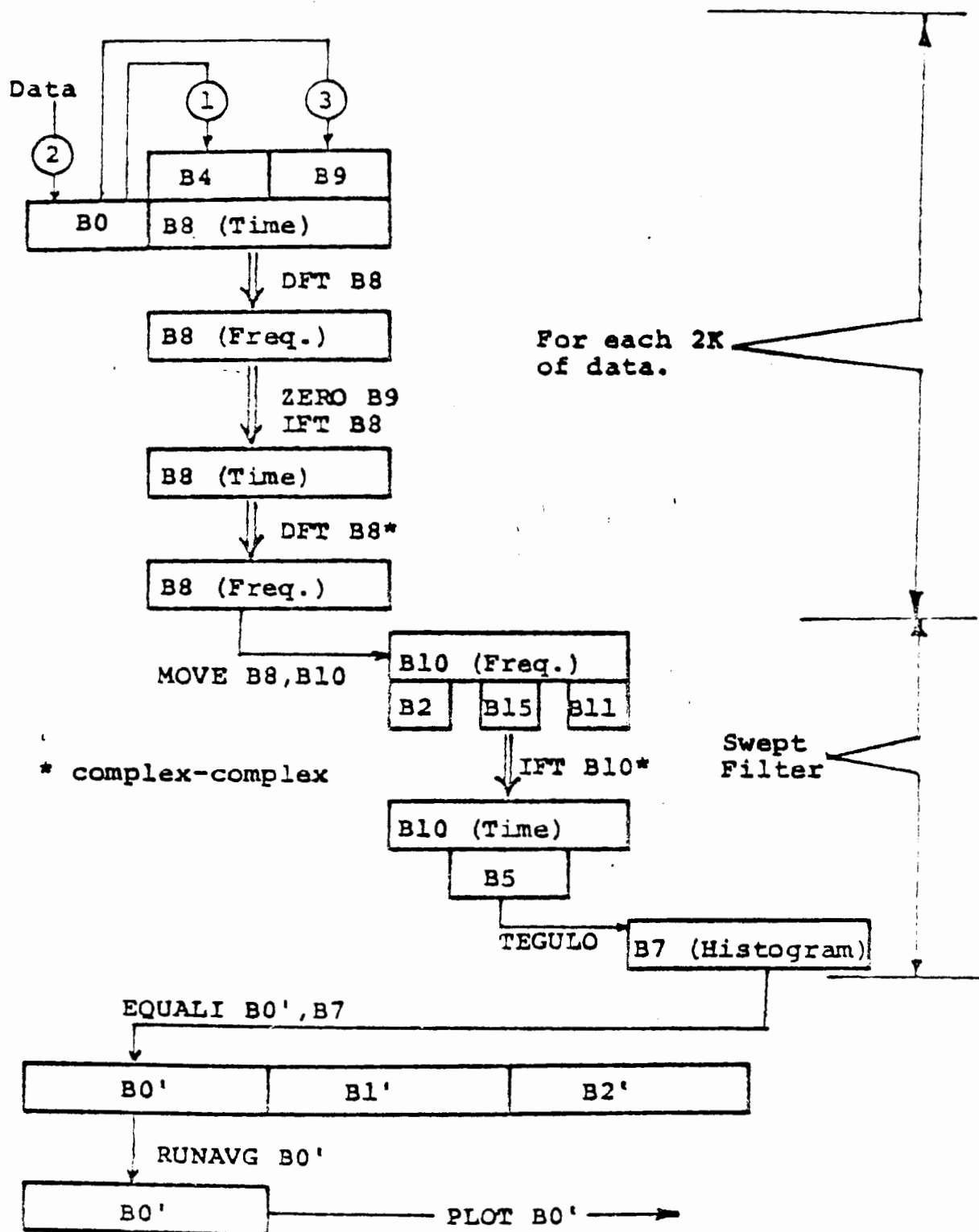
Figure 3

Data Flow For HISCAN

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millisecond savings in time per transform performed. The first complex to complex transform is a DFT of block B8 with the resultant frequency components again being stored in block B8. Repetitive copies of the frequency components of the data are moved to block B10 where an ideal digital narrowband filter (B2, B15, B11) is created. This is accomplished by zeroing the frequency components outside of the bandwidth of the filter. A complex to complex IFT is then performed on block B10. The 4K data block in B10 now represents a narrowband filtered time signal and, if plotted, displays the waxing and wanning nature shown in Figure 1.

To reduce significantly the end effects associated with the discrete inverse fourier transfer, block B5 is defined as the center 2K data points of the 4K block B10. The upper 1K data points and the lower 1K data points are discarded. A rather ingenious method of data flow will recover the information within these points. This will be discussed in the following paragraph. The processing continues from here by applying the zero crossing detection routine, called TEGULO, to block B5. TEGULO determines the instantaneous frequency between positive going zero crossings. It compares this calculated frequency to the known frequencies contained within the narrowband filter. If the calculated frequency is within the band, its associated count stored at an address in block B7 is incremented. Notice that block B7 is 4K in length.

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To evaluate the frequency components from the minimum to the maximum, the narrowband filter is made to scan across the band of interest. Accordingly, after TEGULO has been run, HISCAN loops back to move a copy of the frequency components from block B8 to block B10. The narrowband filter is redefined so that the lowest frequency element is dropped from the filter and the next higher frequency element is added to the filter. This process repeats itself until all frequencies of interest have been scanned by the narrowband filter. HISCAN then loops back to load the next 2K frame of sequential data from the disk. Recall that TEGULO operates on the center 2K data points of the narrowband filtered time signal and discards the lower and upper 1K data points. The information contained within these 1K data points is processed as follows. Block B0 still contains the data loaded into Block B9 from the previous loop. By loading a copy of block B0 into block B4 this information is processed on this pass of the loop. Block B0 is of course loaded with the next sequential 2K data points from the disk and a copy of this is moved to block B9 before processing begins. The sequence is shown below.

```
   ┌───────────────────────────┐
   │                           ↓
| B0  |    |    B4     |   B9       Processed Data Blocks
 _____
|          |    ┌─────┬─────┬─────┬─────┐
|          |    │ 1*  │  2  │  3  │  4  │        2,3
|_____|    └─────┴─────┴─────┴─────┘
                         ╲
                ┌─────┬─────┬─────┬─────┐
                │  3  │  4  │  5  │  6  │        4,5
                └─────┴─────┴─────┴─────┘
                         ╲
                ┌─────┬─────┬─────┬─────┐
                │  5  │  6  │  7  │  8  │        6,7
                └─────┴─────┴─────┴─────┘

                |         B8           |
```
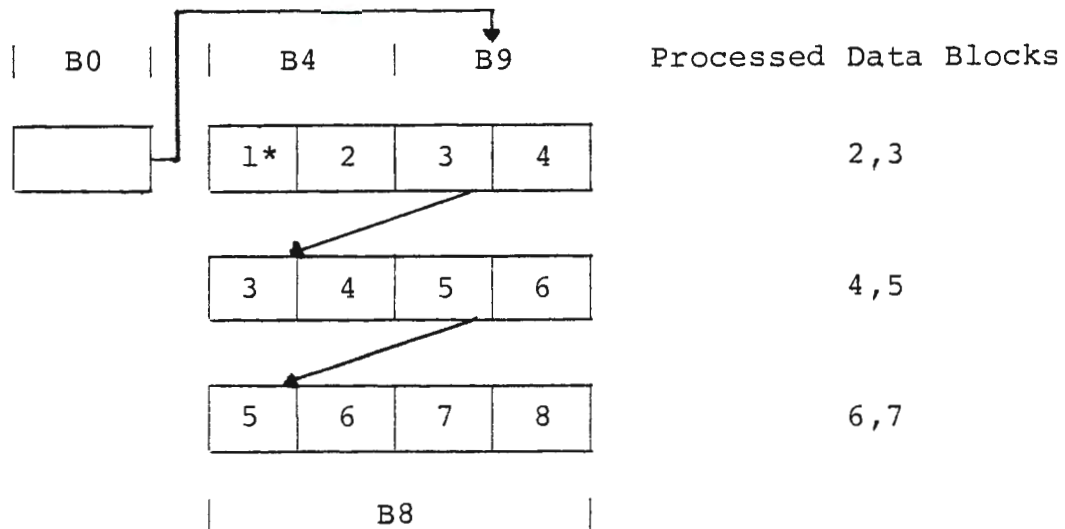
* Numbers refer to sequential lK segments of data.

Observe that the processed data blocks are in time sequential order. This process continues until the specified number of 2K data frames have been read from the disk. When all the data has been read from the disk, a routine called EGUALI is applied to the histogram block B7 to equalize the counts for high and low frequencies. After EGUALI the histogram is smoothed by a routine called RUNAVG. The histogram is now ready to be plotted and appears as previously shown in Figure 2.

The above is an outline of the mechanics of TFA. Recent studies have identified certain key items which have a marked influence on the performance of TFA. These items are discussed below and will be presented in more detail in a future report to be published by Dr. Marmont. They are outlined here with his permission.

To improve the processing capability of TFA a method of reducing the noise power competing with the signal power was developed. Initial discussion of this effective noise reduction method appeared in reference 5 and subsequent improvements in this method were reported in reference 6. The method consists of resampling the data. The data to be analyzed is sampled at a rate of 512 Hz. The samples are stored in a block 4K in length and therefore represent 8 sec in time. This is shown in Figure 4. When the DFT is performed the frequency resolution is 1/8 Hz per DFT frequency element. The DFT frequency element consists of two words, the first word is the real component and the second word is the imaginary component of the Fourier series coefficients. The DFT block represents frequencies from 0-256 Hz. The data will be resampled by a software routine called RESAMP. This routine digitally resamples the data at a rate of 64 Hz or 1/8th of the original 512 Hz sampling rate. Prior to resampling, however, the Nyquist criterion must be satisfied. To accomplish this, the data must be digitally filtered to a 32 Hz band. This 32 Hz band may be located anywhere within the DFT block. For example consider the case where the 32 Hz band from 48 Hz to 80 Hz is to be analyzed. 48 Hz is represented by the 384th DFT element and 80 Hz is represented by the 640 DFT element. The elements from 384-640 are moved down in the DFT block such that element 384 becomes the first element above the DC element. In the process of basebanding the frequencies of interest, consideration must be given to whether the

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B8 = 4K — 4K time samples / sampling rate 512 Hz / 8 seconds

DFT

B8 = 4K — 0-256 Hz / 2 words/element / Resolution 1/8 Hz

DC element
Frequency translation

32 Hz band of interest

Zero

IFT

B8 = 4K — 4K time samples / sampling rate 512 Hz / 8 seconds / 32 Hz frequency band

B10 = 2K

RESAMP

2K time samples
Sampling rate 64 Hz (effective)
32 seconds
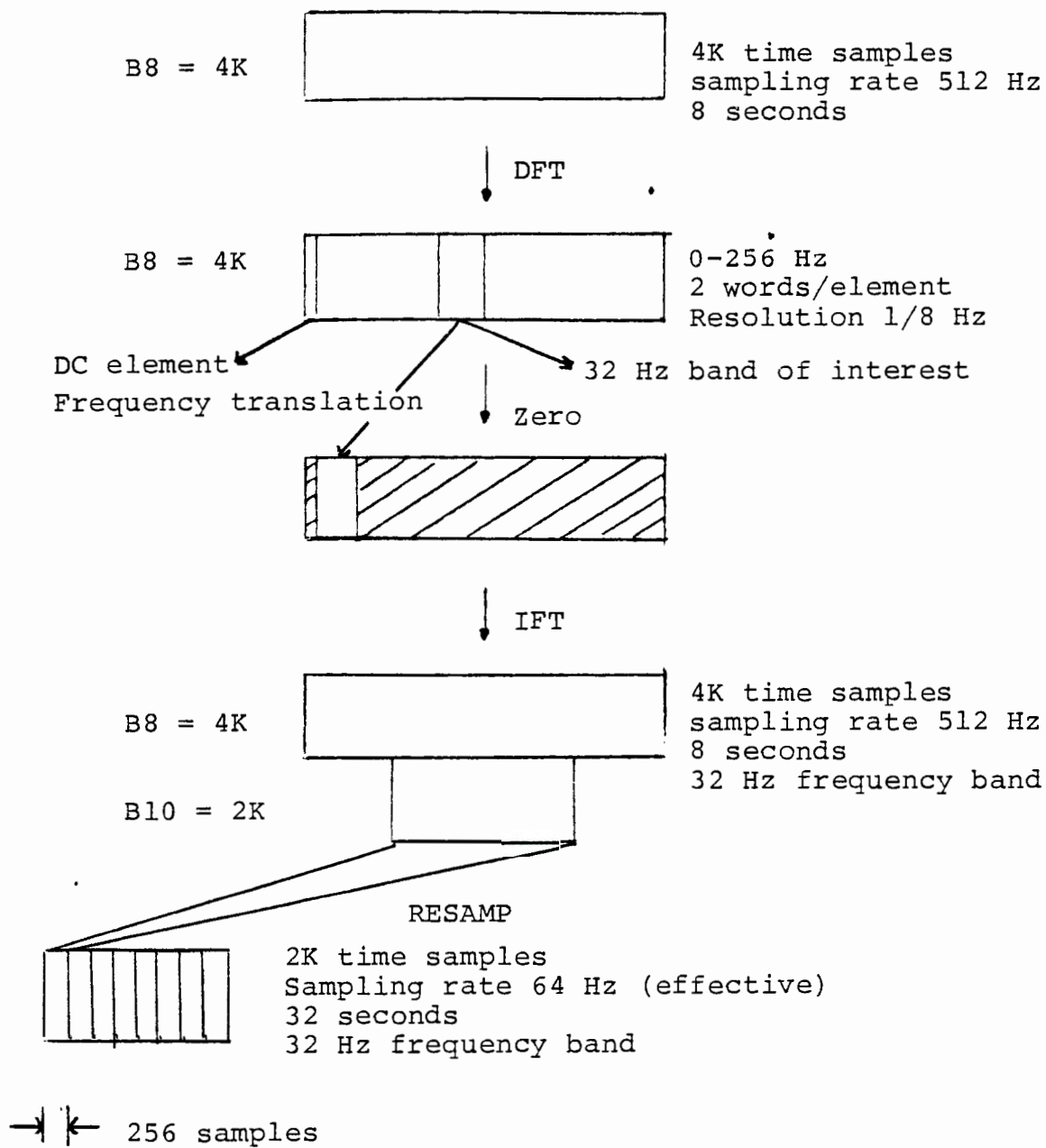32 Hz frequency band

256 samples

Figure 4

Data Resampling

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frequency element is odd. This is discussed in the following paragraph. The DC element and the upper 7/8th of the DFT block are then zeroed. An IFT of the block is then performed resulting in 4K time samples representing 8 seconds in time and containing frequencies from 48-80 Hz. This is shown in Figure 5. In order for the linear interpolation to be valid, there must be at least 10 sample points per cycle (assuming a sinusodial waveform). Recall that on resampled data a 32 Hz band of frequency is basebanded. The 32 Hz band, however, satisfies the Nyquist rate giving only 2 sample points per cycle at the high end of the band. To obtain 10 sample points per cycle the entire range of the scan filter must be no greater than zero to 6.4 Hz (32/5). As a comparison, the bandwidth of the narrowband filter is on the order of 10 frequency elements. For resampled data this is 10/64 Hz. Observe also in Figure 5 that the fractional word count between zero crossings is obtained. In order to maintain with interger arithmatic the numbers are multiplied by 2" during the calculation process. Knowing the time between the words, the period and, hence, the frequency can be calculated. The frequency is then represented as an address in the histogram block. This method provides a 10 fold improvement in the frequency resolution. For example, consider the case where the data is resampled at 64 Hz. For the 4K data block the conventional resolution is 64 DFT elements/Hz. In TFA, however, the requirement of 10 sample points per cycle sets the
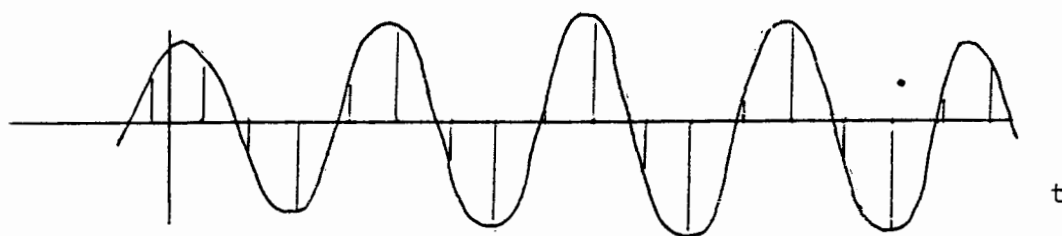
(a) Sampled time waveform
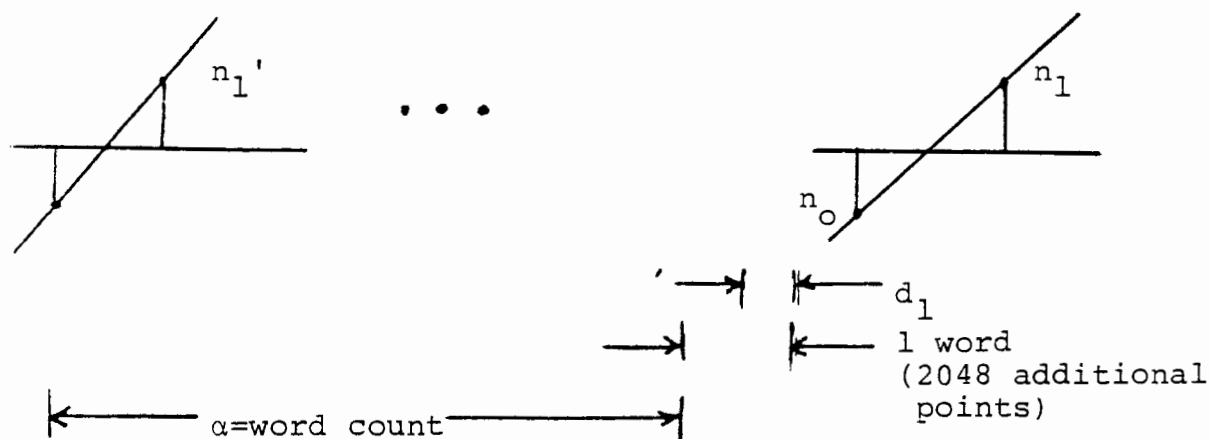
(b) Zero Crossing Interpolation

n_o = negative sample before zero crossing

n_1 = positive sample after zero crossing

d_1 = zero crossing to positive sample point

$d1 = 2048 \dfrac{n_1}{|n_o|+n_1}$ word count
between zero $= \alpha - (1-d_1') + 1 - d_1$
crossings

d_1' = previous d_1 $= \alpha - d_1' - d_1$

Figure 5

Zero Crossing Interpolation

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highest frequency at 6.4 Hz. The 6.4 Hz band represented by the histogram is stored in a 4K block giving 640 histogram points/Hz.

No discussion of TFA would be complete without giving thought to the construction and interaction of the scan filter. The filtering is substantially valid if there are at least 10 consecutive frequency elements in each rectangular window, provided the two 1K end blocks of the resultant 4K IFT block are discarded. This substantially reduces the end effects inherent with the DFT. The effect of the scanning is to average the tendency of the addition of several sinusoids to "pull" the zero crossing measured frequencies to the center frequency. This gives a very linear frequency scale for the histogram block. The filter is made to scan by dropping the lowest frequency element and adding the next higher frequency element. In resampled data this is a change of 1/64 Hz. This method gives equal exposure to all the elements. As HISCAN reads the next 2K block of data from the disk, the noise will be quite different from the previous 2K block of data in magnitudes, frequencies, and phases. Each successive sinusoidal signal in the next new block, however will be substantially the same, except for phase. Hence the successive scans average a mixture of noise components and possible signal in various combinations of amplitude and phase with respect to frequency. Due to the small incremental change in the scan filter (1/64 Hz for resampled data) the frequencies of the components

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change gradually. The range of frequencies for a given scan number in the case of resampled data is very small (10/64 Hz). Although the incremental change and the number of elements included in the scan filter are small, the tegular nature of the IFT's for successive incremental scan positions is experimentally determined to differ markedly. This is shown in Figure 6 where two IFT's, differing only by one DFT element are plotted. Due to the complex nature of the beating phenomenon and the averaging performed by the scan filter, a mathematical analysis of TFA is impractical. An experimental approach to determine the important factors is efficient and effective.

III. REVISIONS TO TFA

To investigate the nature of the Tegules and the feasibil-
ity of a selective comparison for processed output data to
amplitude and constancy of frequency input parameters to en-
hance a weak signal the subroutine which detects the zero
crossings (TEGULO) was modified. Recent unpublished studies
had shown that the input amplitude and constancy of frequency
could be combined to define a selective criteria. The ampli-
tude and constancy of frequency of the associated computed
zero crossings could be compared to the established criteria
to determine if the histogram count should be incremented.
To observe the effect of both high and low amplitudes two new
versions of TEGULO were written. One version (called HISCAN·
DEL) required the amplitudes to be above a callable percentage
of the maximum amplitude to be considered for inclusion in the
histogram and the other version (called HISCAN·XXX) required the
amplitudes to be below a callable percentage of the maximum
amplitude to be considered for inclusion in the histogram.
Both versions established a running average of the change in
frequency (Δf) corresponding to the periods between successive
nagative to positive zero crossings. The length of the running
average could also be changed by a callable parameter. The
instantaneous Δf had to be within the selected range of the
running average to be considered in the histogram. The pro-
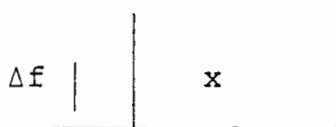grams were set up to show graphically which zero crossings
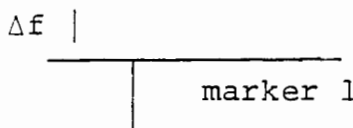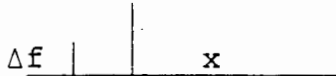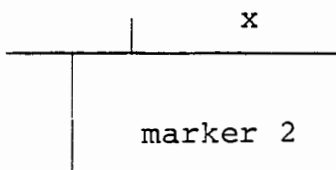
were included in the histogram. To reduce the end effects asso-
ciated with the DFT, only the center 2K samples are resampled.
The routine RESAMP selects every eight sample and stores it in
a new 2K block. It takes eight passes to the loop to fill the
new 2K block. When the storage block is filled it represents
32 seconds in time, and it is transferred to the disk for
permanent storage. The data flow in RESAMP is the same as that
in HISCAN to insure that there is no loss of data. Resampling
thus performs a time compression. The effect of resampling is
to increase the frequency resolution and to decrease the noise
per DFT element. This is apparent when thought is given to
the data flow HISCAN. Recall that HISCAN established the
4K block B8 (Figure 3). With resampled data, which has a
sampling rate of 64 Hz, the 4K block B8 represents 64 seconds
in time. When DFT is performed the frequency resolution is
1/64 Hz. Therefore the frequency resolution has been in-
creased by a factor of 8 and the noise per DFT element has
been reduced by a factor of 8. This increases the effective
S/N ratio. The numerical value of this increase is developed
in the section dealing with Test Procedures and Results.

In the routine RESAMP when the lowest frequency of interest
to be baseband converted is odd, the time domain representation
will be 180 degrees out of phase on every other pass through
the loop. This problem is solved by negating both the real

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and the imaginary Fourier coefficients for every odd number loading of a 2K word data frame.

The zero crossing routine, TEGULO, performs a linear interpolation between the negative to positive data words at each side of the zero crossing. There are four possible outcomes:

Within Δf Range	Within amplitude range	Graphical Display (CRT and/or Plot)
No*	No	
No	Yes	
Yes*	No	
Yes	Yes	

* "DON'T CARE" condition

$$\left|\text{marker 1}\right| \quad < \quad \left|\text{marker 2}\right|$$

Figure 6 shows a typical result.

With the above modifications to HISCAN, the influence of amplitude and constancy of frequency boundaries on enhancing

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the detectabiliby of a weak signal in a noise background
could be experimentally determined.

Starting with element 114
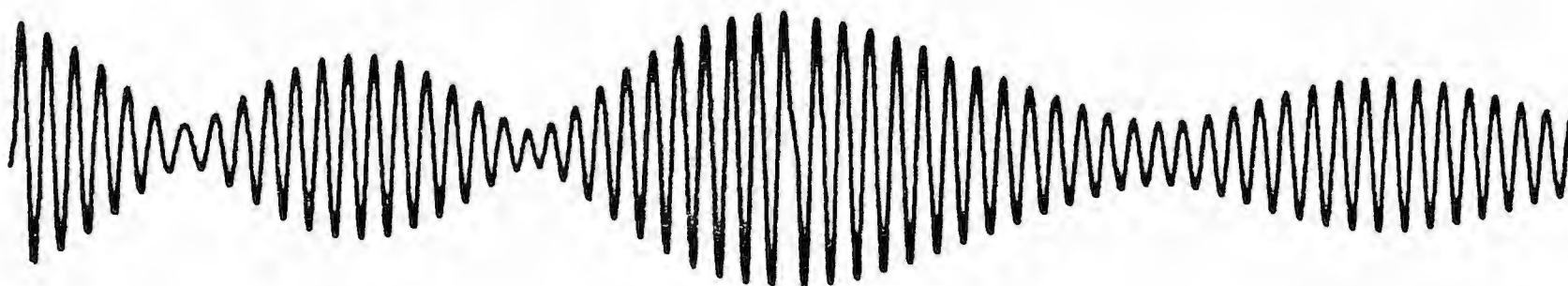
Starting with element 115
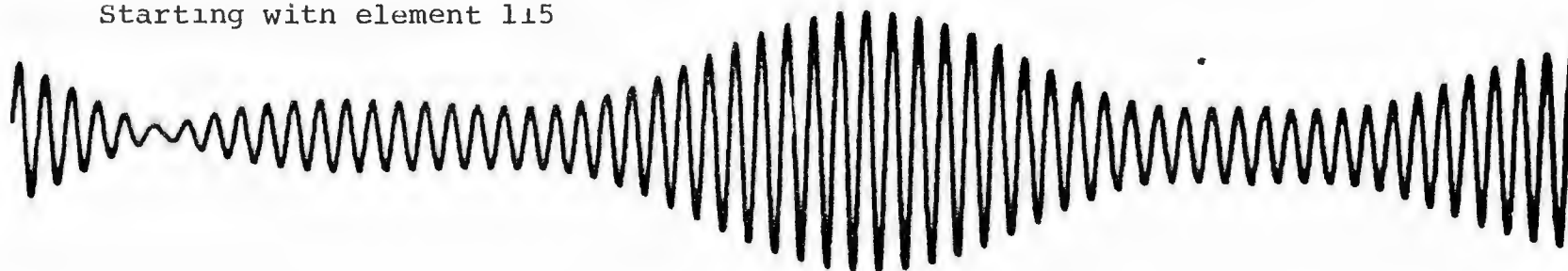
Figure 6

IFT of 10 DFT Elements of Resampled Data
Frequency Content 49.781-49.938 Hz
S/N = -16 db (1 Hz band)

IV. THE DATA

To investigate the nature of the tegules, test signals of various signal to noise ratios were produced. The source of the noise was a Gaussian noise generator. The RMS voltage value of the noise was observed on a true RMS voltmeter. The signal was adjusted to give the desired signal to noise ratio. The noise and the signal were combined by an analog adder and passed through a 4th order Butterworth filter to limit the frequency content from 0-200 Hz. The analog signal plus noise waveform was digitized by a twelve bit A/D converter.

The above method was found to be adequate for large S/N ratios. When a low S/N ratio was desired the signal could not be adequately represented. Due to the dynamic range of the 12 bit A/D converter, a signal at S/N = -20db was represented by only three bits. This can readily be seen by assuming the maximum noise voltage to be roughly 5 times the value of the RMS voltage. With an RMS noise voltage value of 0.4 volts in a 200 Hz band the A/D converter can have a dynamic range of ± 2 volts without experiencing any clipping. The required voltage level of the signal can be calculated from:

$$\sigma_N = 0.4 \text{ volts} \qquad \text{(RMS value of the noise in a 200 Hz band)}$$

$$\sigma_N^2 = 0.16$$

$$\frac{\sigma_N^2}{Hz} = \frac{0.16}{200} \qquad \text{Reduce Bandwidth to 1 Hz}$$

= 0.0008 Watts/Hz (assume 1 ohm resistor)

For a signal to noise ratios of - 20db

S = 0.000008 watts

The amplitude for a sinusoidal signal would then be 0.004

volts. With a 16 bit computer two volts would be represented

by the number 32767. Therefore:

0.004 volts $\simeq 66_{10}$

$$= 102_8 \text{ (octal)}$$

$$= 1 \quad 000 \quad 010_2 \quad \text{(binary)}$$

With only 12 bits for the A/D converter, the lower 4 bits are

lost and the signal is represented by only 3 bits. This is

not sufficient and a method of utilizing the full 7 bits to

represent the signal was sought.

To achieve the maximum precision, the signal and noise

were separately converted to digital form at a sampling rate

of 512 Hz and stored on different disks. A routine called

SIGMA was used to calculate the RMS value of the noise voltage.

SIGMA transforms the noise to the frequency domain and sums

the square of the real and imaginary Fourier coefficients to

find the variance of the noise. The algorithm utilized is

$$\sigma^2 = \frac{1}{M} \sum_{0}^{M-1} \frac{1}{2} \sum_{0}^{N-1} (a_n^2 + b_n^2)$$

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where: M = total number of sample frames

          N = total number of frequency elements per frame

    a_n, b_n = Fourier series coefficients

    σ^2 = variance of the noise (zero mean)

This software calculation compared favorably with the observed meter reading for the RMS value of the noise.

With the RMS value for the noise known a program called TONOIS was used to scale the signal voltage and sum the noise and the scaled signal. In this way seven bits of significance were realized. This data was then resampled by software utilizing the program RESAMP. As discussed in Section II this resulted in an effective sampling rate of 64 Hz. The frequency resolution was increased by a factor of 8 to $\frac{1}{64}$ Hz and the noise per DFT element was reduced by a factor of 8.

V. TEST PROCEDURES AND RESULTS

The test procedures consisted of varying the input para-
meters to HISCAN for the same data and observing the outputs.
The modified versions of HISCAN had eight input paramters as
follows:

P0 = starting DFT element

P1 = the number of DFT elements in the narrowband
     scan filter

P2 = the starting disk address

P3 = the number of 2K reads from the disk

P4 = the number of points to be used in RUNAVG

P5 = the amplitude factor

P6 = the number of words to be included in the
     running average of Δf

P7 = the allowable deviation of the instantaneous
     frequency from the running average of Δf.

P0 through P4 remained constant while P5 through P7 were
varied. P5 was expressed as a fractional part (1/16th)
of the maximum amplitude. Depending on which version of
HISCAN was used, P5 established a level above or below which
the amplitude associated with a zero crossing had to be in
order for its frequency to be counted in the histogram. P6
was expressed as an address offset over which the running
average Δf was established. Recall that block B5 in Figure 3
contains the narrowband filter time waveform. TEGULO is
applied to block B5. The frequency associated with two con-
secutive negative to positive zero crossings is computed.

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The change in frequency Δf is computed by subtracting the frequency associated with the previous negative to positive zero crossing pair from the frequency assoicated with the current negative to positive zero crossing pair. The value of Δf is stored in a new block (B23) in a location relative to the location of its associated zero crossing pair in block B5. B23 is initially zeroed. In this way, the running average can be computed by summing the contents of B23 within the range of addresses specified by P6 and dividing by the number of zero crossing contained within this range. This is done for each negative to positive zero crossing pair. The best maximum look back established was equal to 1/4 the block length of B5 which was 2K. Expressed as an octal address, P6 could vary between $0-4000_8$. A value of 1000_8 was experimentally determined to give the best results. This corresponds to using 1/4 of the block to establish the running average of Δf.

P7 defined the allowable instantaneous frequency diviation (Δf) from the running average of Δf. P7 was expressed as an address offset also. In this case however, P7 was entered as the allowable offset number of bytes. Here a byte is equal to 8 bits of the 16 bit computer word. For example, if a value of 10_8 for P7 was used this reduces to 5 computer words. For resampled data having 640 computer words per Hz, $\Delta f = 1/128$ Hz.

A starting point was established based on past observations. These observations indicated that the version of HISCAN, called HISCAN·DEL, that retained zero crossings associated with amplitudes that were above a callable amplitude level produced better results than HISCAN·XXX which retained zero crossings associated with amplitudes below a callable amplitude level. With this starting point, the parameters P5, P6 and P7 were then varied. Outputs for which there were marked differences were examined on a CRT to correlate the zero crossings retained with the tegular nature of the waveform. The format for the CRT diaplay is shown in Figure 7. Other outputs which appeared interesting for one reason or another, i.e. no change, were also studied.

The results of the tests confirmed the preliminary observation that the version of HISCAN (HISCAN·DEL) which include only data above an amplitude level in the histogram produced better results than the version of HISCAN (HISCAN·XXX) which included only data below an amplitude level in the histogram. HISCAN·DEL also produced better results tnan the original version of HISCAN which did not contain an amplitude or constancy of frequency criteria. A typical result is shown in Figure 8. This result appeared contrary to the past heuristic explanation that the majority of counts for a weak signal in a noise back ground occurred during tegule depressions due to noise beating against noise. Figure 9 has been choosen to demonstrate the relative order of magnitude of the zero

Counts not accepted
for histogram due
to frequencies being
outside of scan filter

counts not accepted
for histogram due
to Δf

count not accepted
for histogram due
to amplitude

counts accepted for
histogram
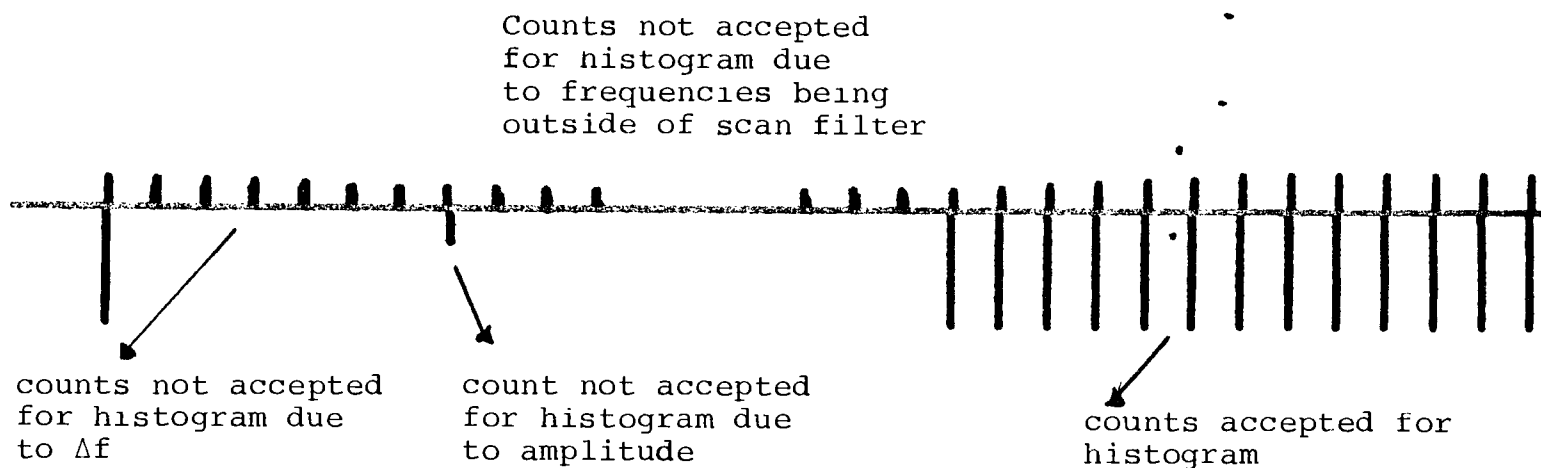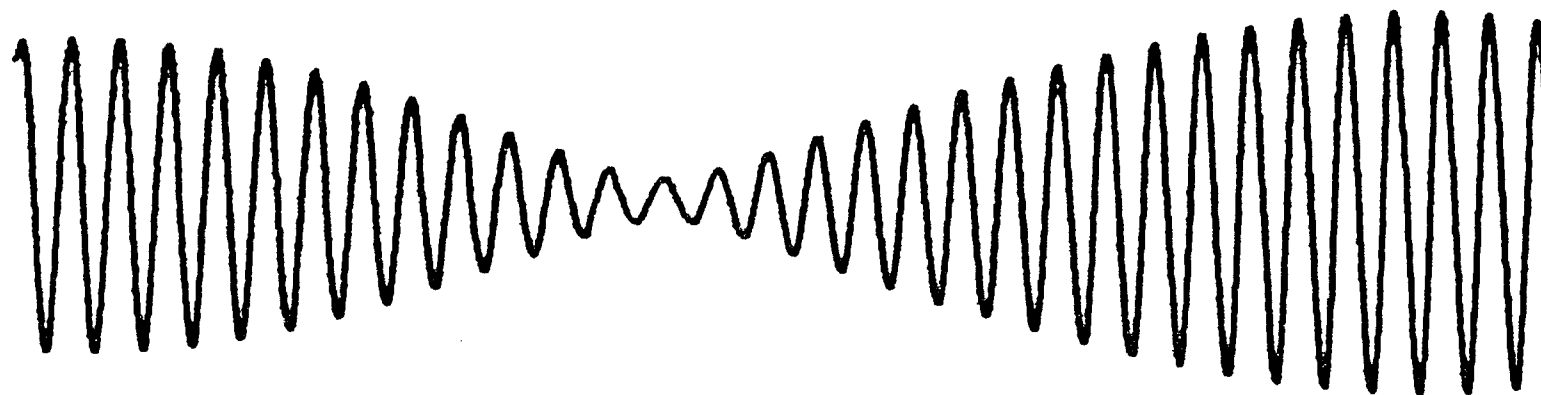
Figure 7

Observation of Tegules with Selective Amplitude
and Constancy of Frequency Acceptance Parameters
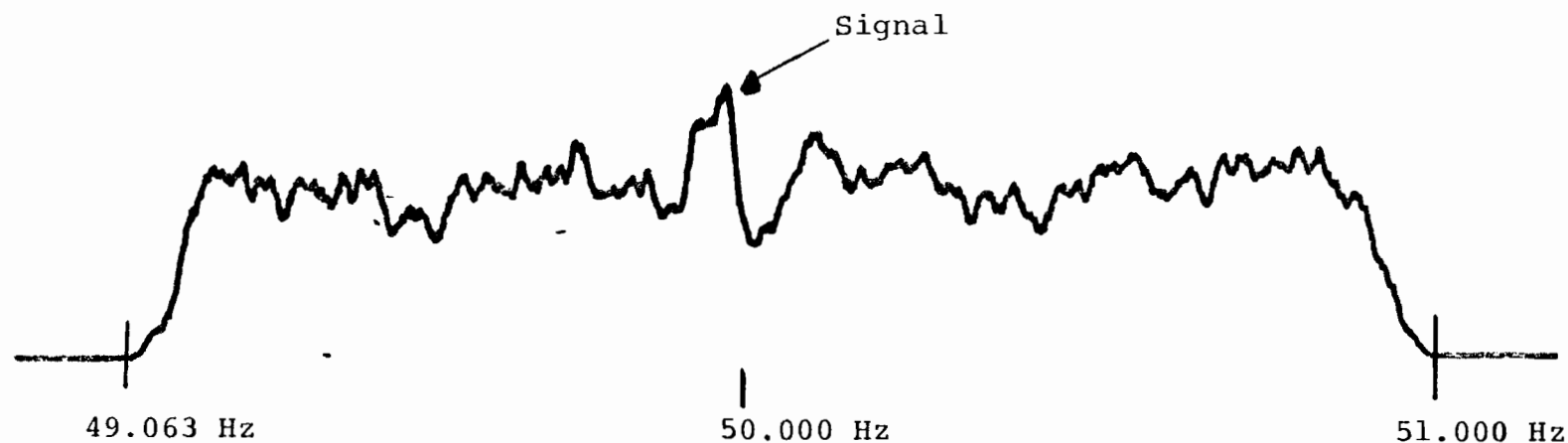
Histogram from original version of HISCAN
S/N = -16 db (1 Hz band) Resampled data
16 2K Reads from disk (Acquisition time: 8.533 min)
S = 50 Hz

Figure 8(a)

Comparison of Histograms For Various Amplitude
And Constancy of Frequency Input Parameters

Note: Larger relating number of
counts associated with tne
Signal (50 Hz)

49.063 Hz   50.000 Hz   51.000 Hz
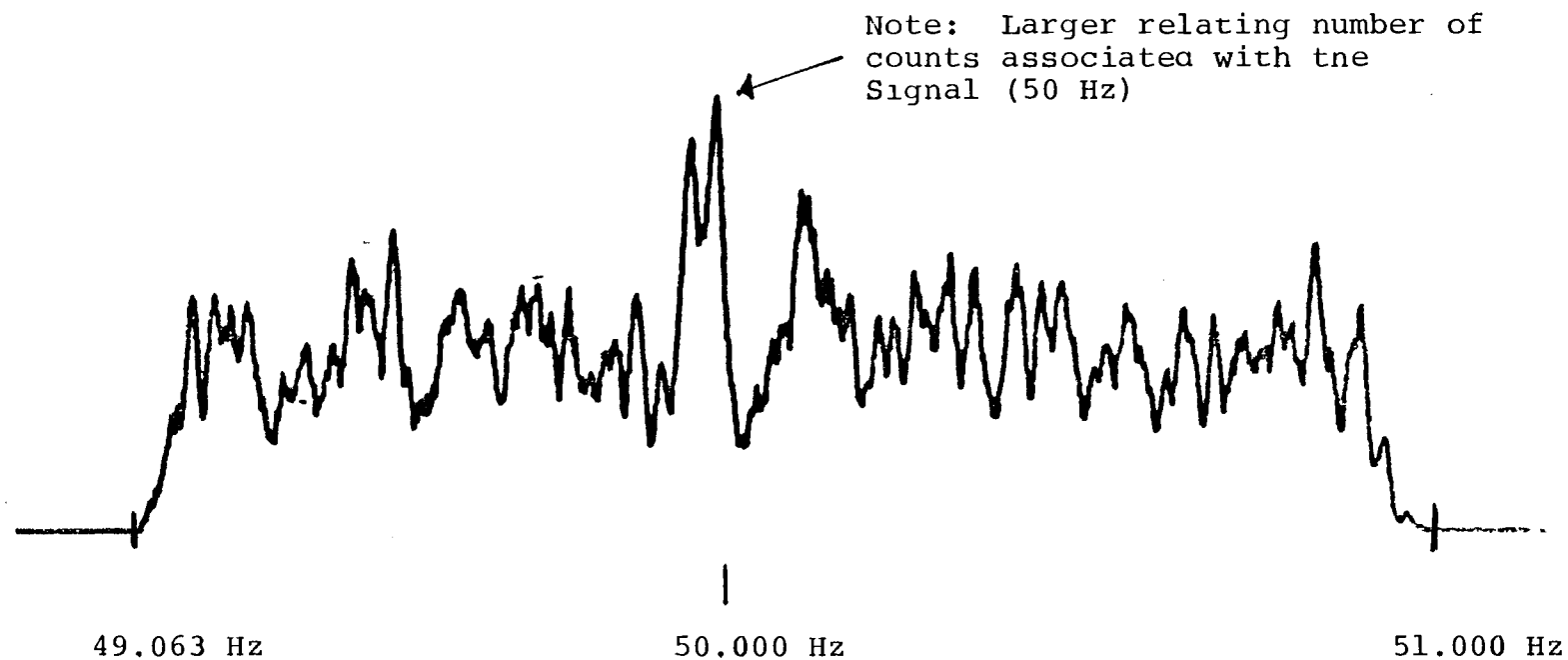
Histogram from HISCAN·DEL. Frequency counted for
Zero crossings whose assoicated amplitudes were $\geq$ 1/2 maximum
amplitude

Data, including acquisition time, is tne same as for
Figure 8(a).

Figure 8(b)

Note: Relative large number of zero crossing counts to be
         included in the histogram.

Figure 9

Histogram Counts Without Selective Comparison
Of Processed Output Data

crossing counts included in the histogram when the amplitude factor has been set to 0 in HISCAN·DEL (all amplitudes are considered for inclusion in the histogram). This is analogous to earlier versions of HISCAN. By comparison Figure 10 shows the relative reduction in the order of magnitude of the zero crossing counts included in the histogram when the data is selectively compared to the input parameters. If the reduction in counts in the histogram is due to "garbage" being discarded, the signal is enhanced. These are typical results and demonstrate the potential for a great processing gain, i.e., enhancement of the signal counts, provided the zero crossings not considered for count have a low probability of containing the signal. This probability cannot be determined analytically. The computer must be used to obtain the numerical results. Time was not available to compute this probability and to include it in this thesis. A proposed method for determining this probability is included in the following section.

Evaluation of the test results revealed that it was possible to decrease the overall number of counts in the histogram by a comparison of the processed output data to an input amplitude and constancy of frequency criteria and at the same time to enhance the signal. This is shown in Figures 11 and 12. In Figure 11 the input parameters were

$$P5 = 12_8 \quad (5/8\text{th}) \qquad P6 = 1000_8 \qquad P_7 = 10_8$$

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Frequencies counted for zero crossings whose
associated amplitudes > 5/8th of maximum amplitude
and whose $\Delta f \leq 1/128$ Hz
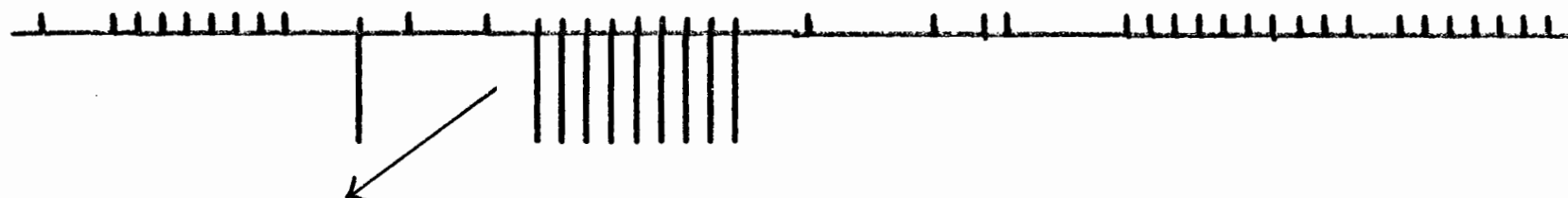
NOTE: Relative reduction in zero crossing counts
to be included in the histogram

Figure 10

Histogram Counts With Selective
Comparison Of Processed Output Data
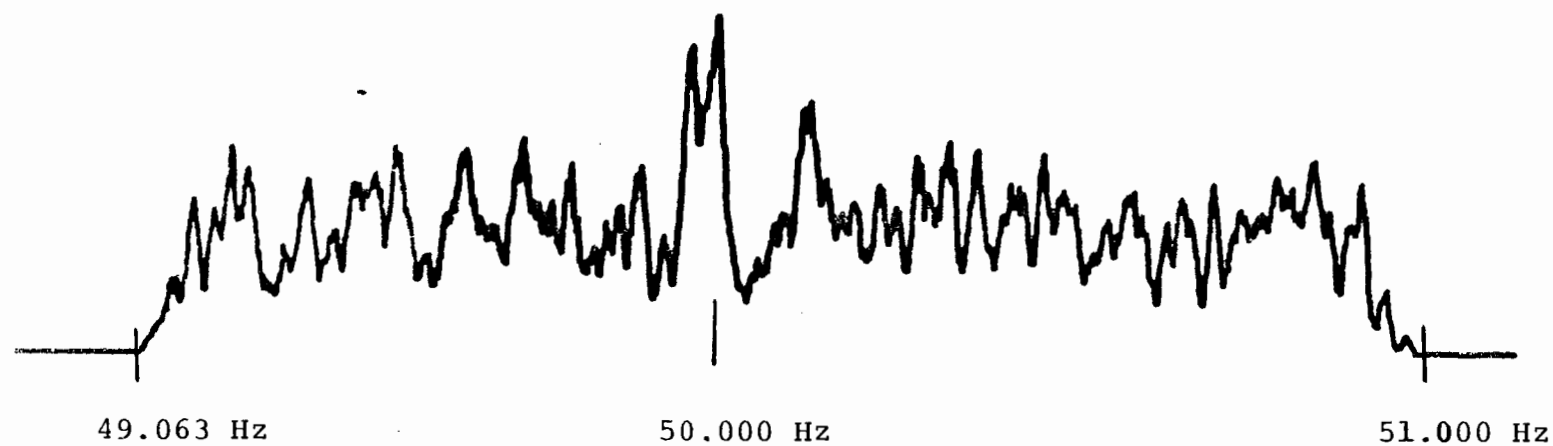
49.063 Hz   50.000 Hz   51.000 Hz

Histogram from H1SCAN·DEL.
S/N = -16 db (1 Hz band) Resampled data
16 2K Reads from the disk (Acquisition time 8.533 min)
Signal = 50 Hz

Figure 11
Histogram For Amplitudes > 5/8th Maximum
$\Delta f \leq 1/128$ Hz
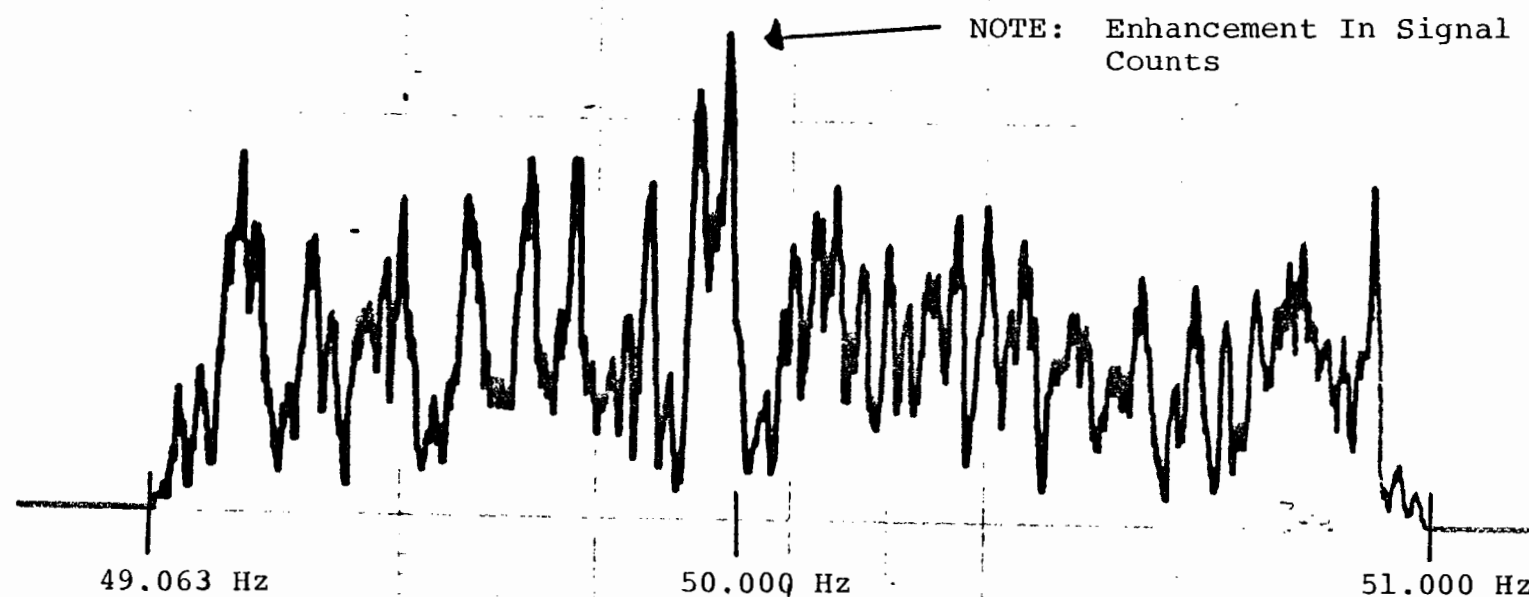
NOTE: Enhancement In Signal Counts

49.063 Hz   50.000 Hz   51.000 Hz

Histogram from H1SCAN·DEL
S/N = -16 db (1 Hz band) Resampled data
16 2K Reads from the disk (Acquisition time 8.533 min)
S = 50 Hz

Figure 12

Histogram For Amplitudes > 6/8th Maximum
$\Delta f \leq 1/128$ Hz

While in Figure 12 the input parameters were

$$P5 = 14_8 (6/8th) \qquad P6 = 1000_8 \qquad P7 = 10_8$$

For this particular case an increase in the amplitude level above which the counts were included in the histogram, improved the histogram. The selection process therefore resulted in a "processing gain". In cases such as this, where a high count for a valid signal occurred, examination of the zero crossing plots (Figure 7) indicated the following:

1. Δf was small over an appreciable interval.

2. The amplitude was relatively large.

The fact that the large amplitudes enhanced the signal was confusing at first. The heuristic explanation of how TFA works has always included the concept that the signal was more likely to be observed during the tegule depressions. In the case of resampled data, the effective signal to noise ratio per 10 DFT spectral elements used in each scan is increased. In the previous section it was shown that for a S/N = -20 db (in a 1 Hz band)

$$V_{SIG} = 0.002828 \text{ volts RMS}$$

$$\frac{\sigma_N^2}{Hz} = 0.0008 \quad \frac{WATTS}{Hz}$$

As a result of resampling the frequency resolution is increased to 1/64 Hz. Since a scan width of 10 DFT spectral elements was used, the scan bandwidth is reduced to 10/64 Hz from 1 Hz.

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Therefore (for S/N=-20db before resampling), after resampling:

$$\sigma_N^2 = 0.0008 \; \frac{WATTS}{Hz} \; X \; \frac{10}{64} \; Hz$$

$$\sigma_N^2 = 0.000125$$

$$\sigma_N = 0.01118$$

$$V_{SIG} = 0.002828 \; RMS$$

$$\frac{V_{SIG}}{\sigma_N} = 0.2529$$

$$\frac{S}{N} = -11.94 \; db$$

This is an 8.06 db improvement in the effective S/N ratio. For data originally at S/N of -16db(in a 1 Hz band) which was the case for the majority of the test runs, the effective signal to noise ratio was increased to - 7.94 db. Therefore

$$\frac{V_{RMS}}{\sigma_N} = 0.401 \quad \text{(effective)}$$

rather than the voltage ratio of 0.158 associated with -16 db.

Reference 6 reported on the extremely short acquisition time required for TFA as compared to systems presently used by the Navy. This short acquisition time is one of the salient features of TFA. Its importance cannot be overemphasized. To demonstrate this capability, the acquisition time for Figures 8, 11 and 12 (8.533 minutes for -16 db S/N in a 1 Hz

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band) was reduced by a factor of 1/2 to 4.267 minutes and the analysis repeated. The results are shown in Figure 13. The 50 Hz signal still received the largest number of counts in the histograms of the HISCAN·DEL version. Future work needs to be directed towards establishing a minimum acquisition time for a given signal to noise ratio.

In summary the results demonstrated that it is feasible to compare the processed output data to amplitude and constancy of frequency input parameters to enhance the signal. For test data at a $S/N = - 16$ db (1 Hz band), the histogram counts assoicated with the signal was enhanced when the amplitude was 5/8ths or 6/8ths of the maximum amplitude and the change in frequency was small over an appreciable interval.

Signal

49.063 Hz   50.000 Hz   51.000 Hz
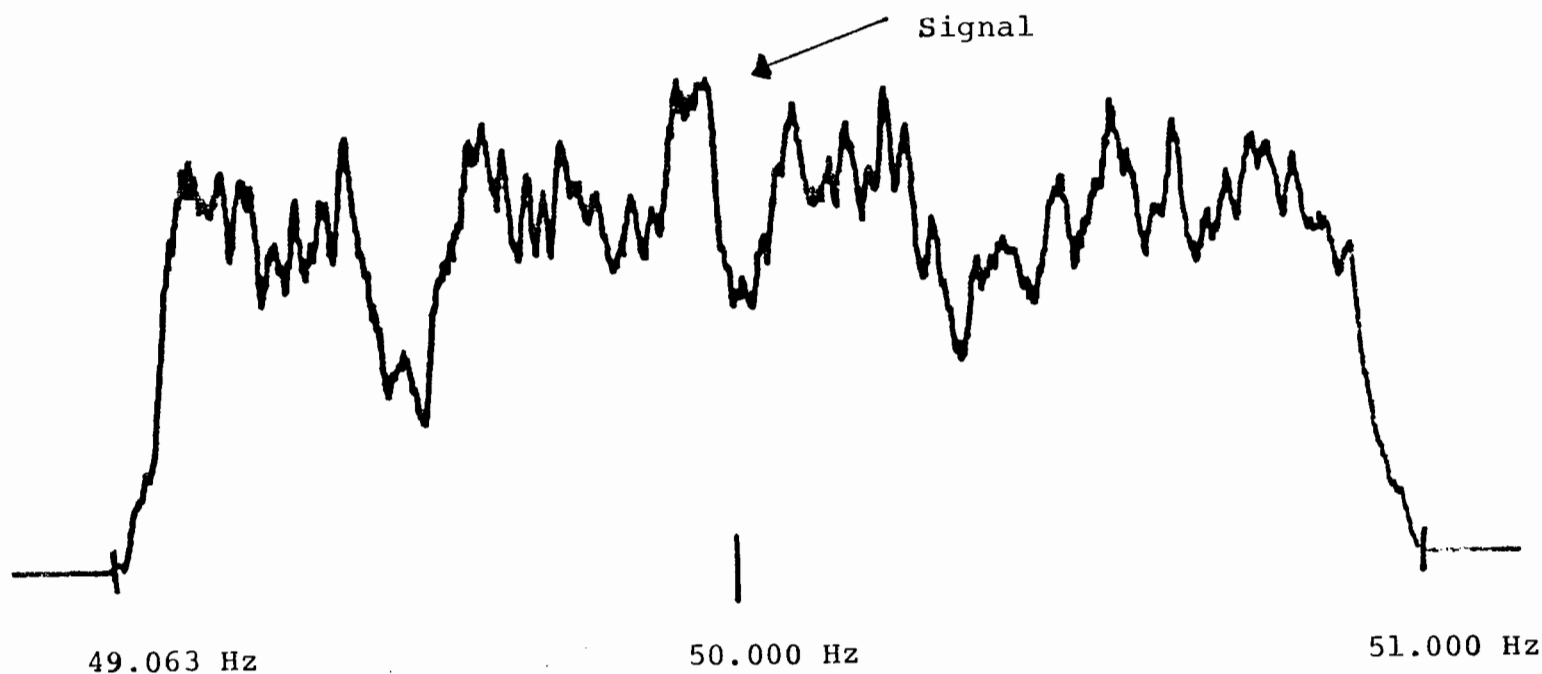
Histogram from original version of HISCAN
S/N = -16 db (1 Hz band). Resampled data
8 2K reads from the disk (Acquisition time 4.267 min)
Signal = 50 Hz

Figure 13(a)

Reduced Acquisition Time Processing

49.063 Hz   50.000 Hz   51.000 Hz
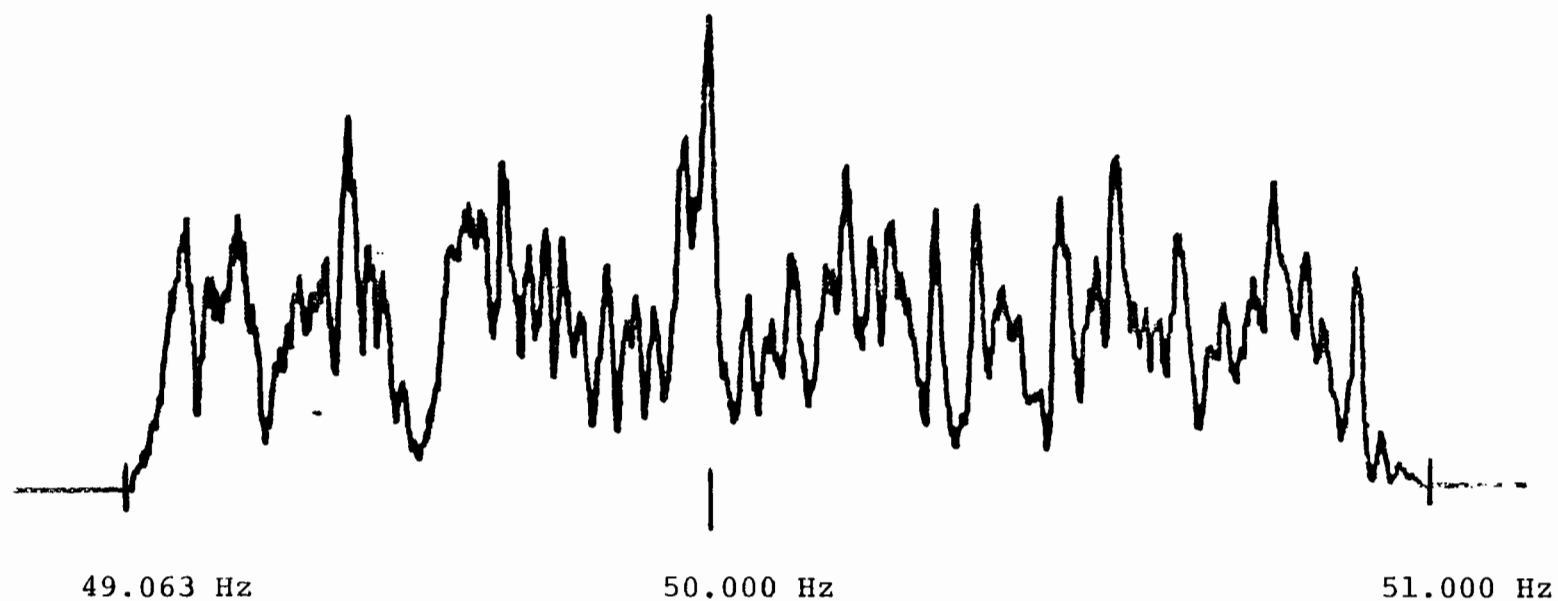
Histogram from HISCAN·DEL. Frequencies counted
for zero crossings whose amplitudes were $\geq$ 1/2 maximum
Data is the same as for Figure 13(a)

Figure 13(b)

49.063 Hz   50.000 Hz   51.000 Hz
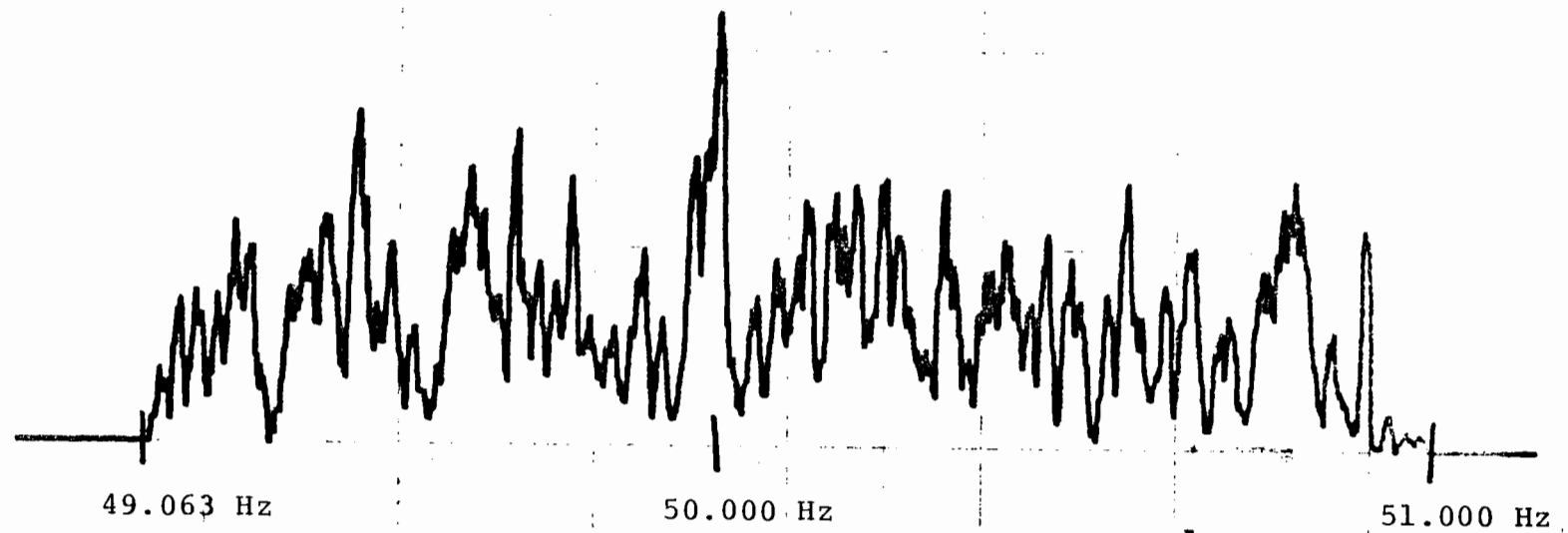
Histogram from HISCAN.DEL. Frequencies counted
for zero crossings whose amplitudes were > 5/8 maximum
S/N = -16 db (1 Hz band) Resampled data
8 2K reads from tne disk (acquisition time 4.267 min)
Signal = 50 Hz

Figure 13 (c)

49.063 Hz   50.000 Hz   51.000 Hz

Histogram from HISCAN·DEL. Frequencies counted
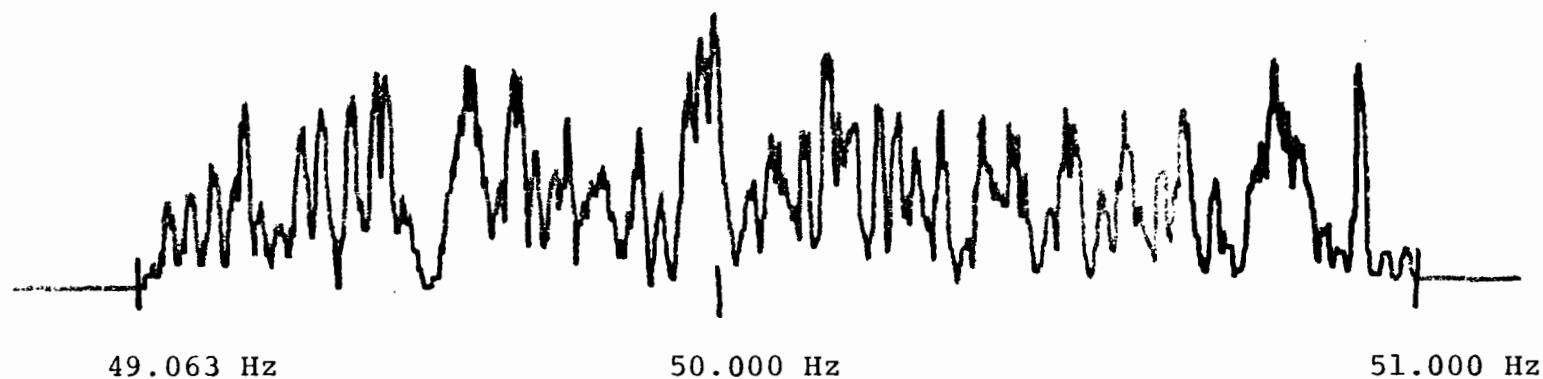for zero crossings whose amplitudes were $\geq$ 6/8 maximum
Same data as Figure 13(c)

Figure 13(d)

VI.   CONCLUSIONS AND RECOMMENDATIONS

The test results demonstrated that it is feasible in TFA to enhance a weak signal in a noise background by selecting input parameters against which the results of processing are to be compared for acceptability. In this context then, selective comparison of processed output data results in a "processing gain". The fact that better results are obtained when amplitudes of 5/8ths or 6/8ths of the maximum are selected for the histogram counts can be explained in the following manner. By resampling the data, it was shown that the signal to noise ratio in the scan band is increased by a factor of 8.06 db. Therefore the RMS signal to noise voltage ratio in the scan band for an original signal to noise ratio of -16 db in a 1 Hz band is increased from 0.158 to 0.401.

The scan band consisted of 10 complex spectral elements. Assuming for simplicity a signal with no DFT leakage, each of the 10 complex spectral elements represents noise with the exception of one element which represents a combination of signal and noise.

As the narrowband filter scans across the frequencies of interest, the noise changes each time the lowest DFT element is dropped and the next higher DFT spectral element is added. The signal, however, does not change. The frequency, amplitude, and phase of the signal are constant for the particular read of data from the disk. When a new block of data is read

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from the disk, the noise is of course different, but the signal differs only in phase (assuming a constant source and neglecting effects of the transmission medium). Accordingly, when the narrowband filter of 10 complex spectral elements scans across the signal there are ten scans during which the noise is changing but the signal is not changing. Since the effective RMS signal to noise voltage ratio in the scan band is 0.401 (for -16 db S/N) and since the amplitude of the noise is changing, it is highly probable that the signal amplitude will be greater than the noise amplitude for a number of scans. Under these conditions, when the signal amplitude is higher than the noise amplitude, the signal will "capture" the noise. This is the same capture effect associated with FM transmissions. The high amplitude frequency component will dominate. This will result in several sequential negative to positive zero crossings being at or near the signal frequency. With this in mind, the desirability of acceptable processed data also based on a relatively slow rate of change of frequency becomes apparent. The signal frequency as measured by zero crossings will receive a relatively larger number of counts than the noise components. The concept of "capture" appears to be a reasonable explanation to the correlation of certain input parameters with the histogram output.

It is recommended that since Reference 6 has already demonstrated the capability of TFA to detect weak signals in

the ocean environment with short acquisition times, that a prototype tegulometric frequency analyzer be developed and tested. As a follow-on to this thesis, it is recommended that the zero crossing routine TEGULO be modified to compute an "enhancement index" of a signal as a function of amplitude and constancy of frequency. One possible way to compute this enhancement index is to record the noise and signal on separate disks, as previously discussed, and to resample the two disks separately. Before scaling and combining the signal with the noise, HISCAN, with selected input parameters, can be run on the noise. The histogram would indicate how many counts at the signal frequency were due to noise alone. After combining the signal and the noise, the histogram with the same input parameters would indicate the number of counts at the signal frequency due to signal plus noise. The difference between these two counts would be a measure of the enhancement index of the signal. The probability of a signal being enhanced for a particular amplitude criteria and a given Δf would require computing the enhancement index for the case where all amplitudes are considered for analysis. This would be followed by computing the enhancement index for amplitudes above and below the amplitude level criterion. The ratio on the enhancement index above the amplitude level to the enhancement index for all amplitudes would be an indication of the probability of the signal counts being contained in the amplitudes above the level. In a similar way the probability of

the signal counts being contained in the amplitudes below the level can be computed. As a graphical aid, the plotting routine can be modified to indicate which counts for the histogram are within a specified frequency range of the test signal. The above modifications would supply numerical data from which the optimum selection of the input parameters and a valid explanation of the workings of TFA could be obtained.

Work performed on test data with a S/N ratio of -20 db (1 Hz band) revealed that the counts associated with the signal were not always the maximum count on the histogram. Evaluation of sequential processing results highlighted the random nature of the noise and the constancy of the signal frequency. It is recommended that for extremely low S/N ratios a correlation technique be developed for TFA. It is felt that a correlation capability would greatly improve the sensitivity of TFA to detect a signal at weaker than -20 db S/N ratio (1 Hz band). The implementation of this correlation feature would not be difficult. One possible way of achieving a type of correlation would be to define two blocks (double precision) each parallel to the histogram block. One block would contain a product and the other block the sum of the products. The first histogram block would be moved to the product block. The product block would then be multiplied by the histogram block for the next section of data with the double precision result being stored in the product block. The product block would then be normalized and shifted down

to a single precision word. The product block would be added
to the sum block (initially all zeros). Again the sum would
have to be normalized and shifted down to single precision
after each addition to prevent overflow. With the observa-
tions made to date this correlation like function holds great
promise in increasing the sensitivity of TFA.

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